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# Surface chlorophyll variability in the Drake Passage region of the Southern Ocean

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# **Surface chlorophyll variability in the Drake Passage region of the Southern Ocean**

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An Undergraduate Honors Thesis for the Department of Geological Sciences  
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**ABSTRACT:**

The Southern Ocean, the ocean surrounding the Antarctic continent, supports a diverse array of biological species and unique food webs. Given the important role of phytoplankton in Southern Ocean food webs and their influence on the global carbon reservoir, it is of interest to know whether their abundance has changed over time. Chlorophyll is a pigment present in all photosynthesizing phytoplankton that can be used to estimate the biomass and productivity of phytoplankton at a given time and location. This study analyzes surface chlorophyll variability in the Drake Passage region of the Southern Ocean using underway fluorometer derived chlorophyll from the ARSV Laurence M. Gould (2002-2015), along with satellite derived chlorophyll-a estimates from the MODIS sensor. We observe an austral fall bloom in the underway fluorometer record, ranging from 40%-100% of the maximum bloom concentration in a given year. This bloom is significant due to its timing and magnitude, and due to its absence from the recent relevant literature. We propose that recent studies failed to observe a fall bloom in this region due to reliance on satellite-derived estimates of chlorophyll for which there exist very few valid estimates in the Drake Passage during the austral fall. Analysis of MODIS estimates of chlorophyll also revealed that this sensor systematically underestimates chlorophyll concentration in the Drake Passage region. Lastly, a weak statistical relationship between surface

ocean  $p\text{CO}_2$  and fluorometer-based chlorophyll was observed in the Drake Passage. We suspect that this weak relationship is due to the opposing effects of the thermally driven component of  $p\text{CO}_2$  and the component of  $p\text{CO}_2$  due to changes in total dissolved inorganic carbon.

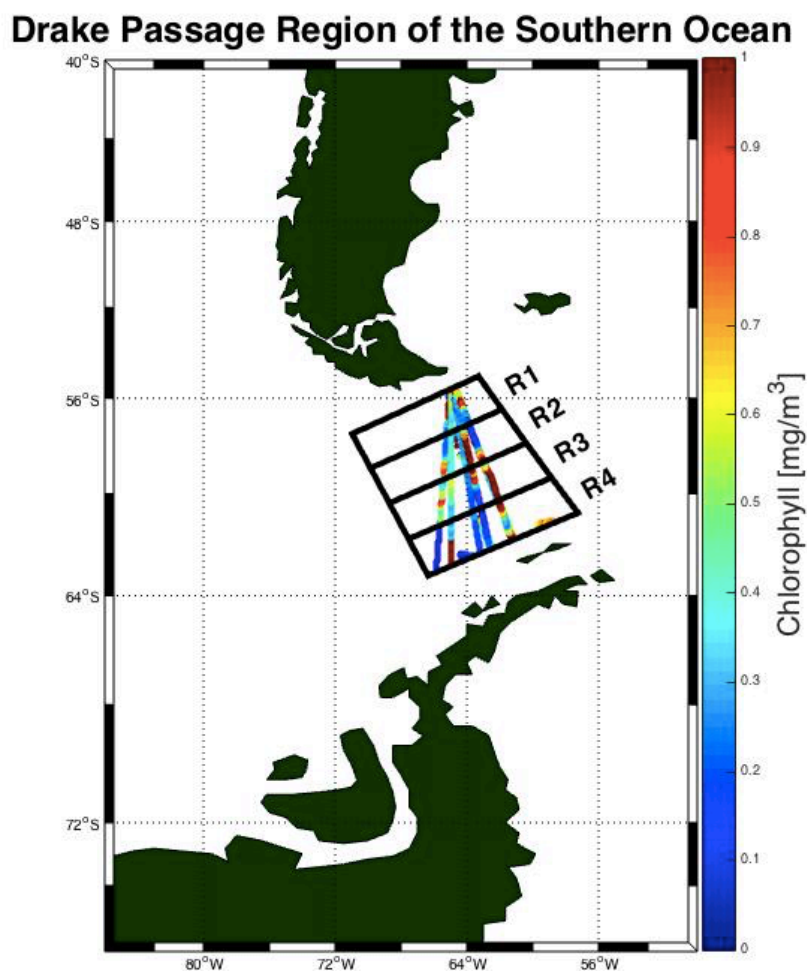


## **INTRODUCTION:**

The Southern Ocean, the ocean surrounding the Antarctic continent, supports a diverse array of biological species and unique food webs (Atkinson et al., 2004). The Southern Ocean is historically under-sampled with respect to biology and biogeochemistry, but since 1997, satellites measuring ocean color have provided estimates of the surface chlorophyll concentration in this region (Lovenduski and Gruber, 2005). Chlorophyll is a pigment present in all photosynthesizing phytoplankton and can be used to estimate the biomass and productivity (carbon fixation) of these phytoplankton at a given time and location (Arrigo et al., 2008).

Given the important role of phytoplankton in Southern Ocean food webs, it is of interest to know whether their abundance has changed over time. Sitting at the base of the food chain, phytoplankton abundance can greatly affect the entire oceanic ecosystem. Unfortunately, detection of temporal variability in Southern Ocean surface chlorophyll via satellites is hampered by cloudiness – satellites cannot see through clouds, and the Southern Ocean is a region with fairly persistent cloud cover. Repeat observations of underway, surface ocean chlorophyll fluorescence have been collected on board the Antarctic Research and Supply Vessel Laurence M. Gould while it traverses the Drake Passage region of the Southern Ocean (up to 20 crossings per year) between the southern tip of South

America and the northern tip of the Antarctic Peninsula (Figure 1, Sprintall et al., 2012). Data has been collected since 2002 and collection continues through the present day. This fluorescence data can provide a means to estimate spatial and temporal variability in surface ocean chlorophyll even during cloudy times.



**Figure 1: The Drake Passage region of the Southern Ocean can be seen here divided into four regions to facilitate comparison and analysis. Colors represent surface chlorophyll fluorescence, as measured by the underway fluorometer in 2014.**

Phytoplankton abundance and variability has globally reaching implications, especially in the Southern Ocean. Here, the subduction of mode and intermediate water formation brings under-utilized nutrients to the thermocline of the subtropics, ultimately fueling low-latitude biological productivity (Sarmiento et al., 2004). Further, phytoplankton productivity plays a significant role in setting the vertical gradients of oceanic carbon (Sarmiento and Gruber, 2006).

The Southern Ocean is also a particularly interesting region to study because of its unique circulation and biogeochemistry. The zonally-unbounded Southern Ocean permits a circumpolar current, the Antarctic Circumpolar Current (ACC), that carries approximately 140 Sv of water through the Drake Passage, making it the world's largest ocean current (Steele et al., 2010). The strongly westerly winds that drive this circulation result in northward surface Ekman transport of water, driving strong upwelling south of the ACC (Steele et al., 2010). This causes the overturning of a cell of water that is referred to as the Deacon Cell.

Another important circulation feature in the Southern Ocean is the Antarctic Polar Front (PF). The Antarctic Polar Front is the location where northward moving surface waters subduct below Subantarctic waters; hence, there is considerable mixing at this front (Moore et al., 1999). The Polar Front is also interesting because of the physical-biological interactions on the mesoscale that

can cause phytoplankton blooms (Moore and Abbott, 2000). These interactions cause phytoplankton blooms by increasing nutrient concentrations in the surface ocean. Increased surface ocean nutrient concentrations can occur by (1) vertical mixing of waters or (2) localized upwelling from topographically induced “mesoscale meandering” of the PF (Moore and Abbott, 2000). This is particularly important in the Southern Ocean because of the distribution of nutrients there. Phytoplankton in the Southern Ocean typically are limited by sunlight and micronutrients (Lovenduski, 2007). Since there is usually an ample amount of macronutrients for phytoplankton, blooms frequently occur where there is an introduction of limited micronutrients, such as iron. The interactions around the PF are one of the main ways limited micronutrients like iron can be introduced to the surface ocean and stimulate phytoplankton blooms.

Here, we analyze the temporal and spatial variability in Southern Ocean chlorophyll measured via the Laurence M. Gould’s underway fluorometer and via the MODIS satellite. We further investigate the relationship between surface chlorophyll and  $p\text{CO}_2$ .

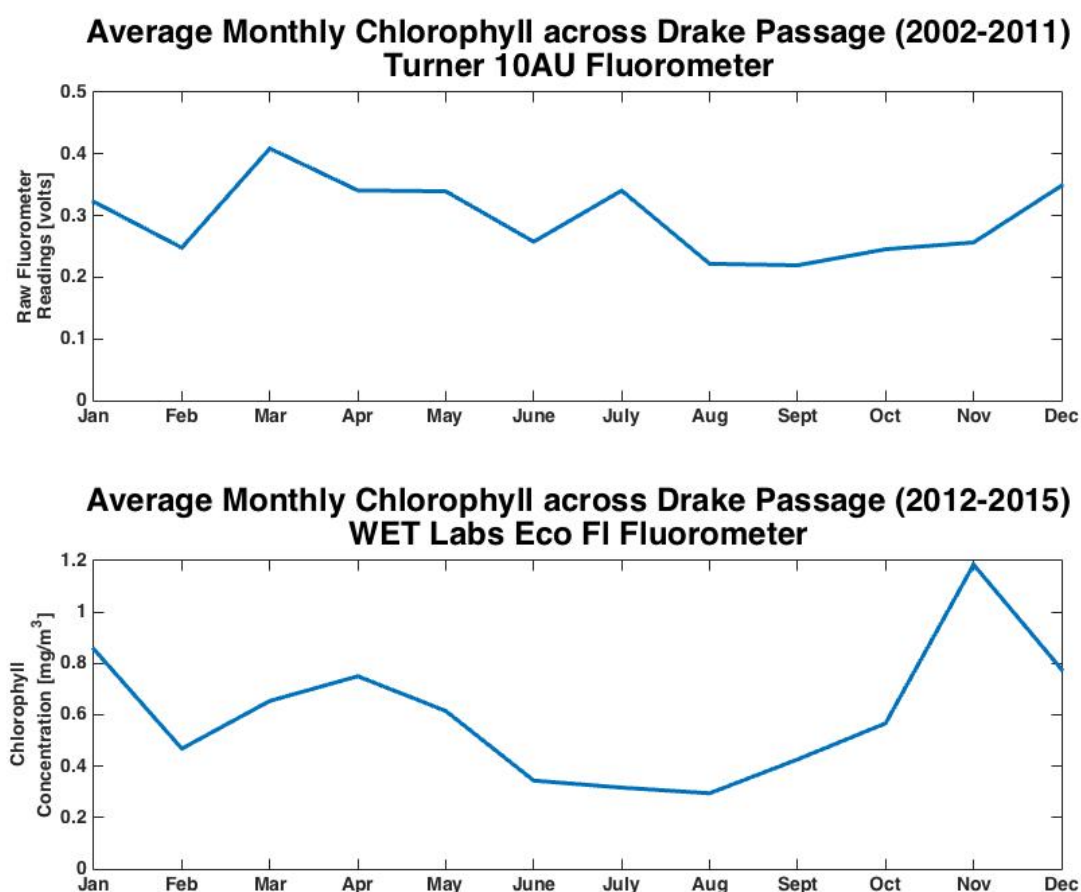
## **METHODS:**

### **Underway Fluorometer:**

In-situ chlorophyll and continuous underway fluorescence have been measured aboard the Laurence M. Gould since 1998 as a part of the Palmer Station Antarctica Long-Term Ecological Research Program (PAL LTER). Figure 1 shows surface chlorophyll measured by the underway fluorometer in the Drake Passage in 2014 along the Laurence M. Gould's resupply route to and from Palmer Station. Here, the Drake Passage is divided into 4 regions, using a method adopted from Munro et al. (2015), where the sampling grid is oriented roughly parallel to the PF, the main jet of the ACC. The PF typically lies on the boundary between Regions 2 and 3 (Munro et al., 2015).

Two different underway fluorometers are responsible for the Laurence M. Gould's fluorescence data set. From 2002-2011, the device recording underway fluorescence was a Turner 10AU fluorometer. However, from 2012-2015, a WET Labs Eco FL fluorometer was the device recording underway fluorescence. The fluorescence data from the Turner fluorometer was never calibrated with a chlorophyll stock onboard the Laurence M. Gould. As a result, it is not possible to convert these fluorescence measurements, which are in raw units of volts, into units of chlorophyll (i.e., we do not have a chlorophyll stock and calibration curve for the Turner fluorometer). Fortunately, the data collected by the WET Labs

fluorometer have already been converted into units of chlorophyll and hence will now be referred to as chlorophyll. While this complication prevents the comparison of fluorescence throughout the entire time-series, it does not render the Turner data useless. The Turner fluorometer still possesses the ability to measure variability, though it cannot conclude anything in terms of chlorophyll magnitude.



**Figure 2: Averaged monthly chlorophyll across Drake Passage from the two different fluorometers. Above is the data from the Turner 10 AU fluorometer that was never calibrated and below is the data from the WET Labs Eco FL fluorometer which is in units of chlorophyll.**

Consequently, the satellite estimates of chlorophyll will only be compared with the fluorescence data from the later half of our data set. As can be seen in Figure 2, the data collected by the two fluorometers are distinctly different in terms of magnitude, while they are mostly similar in terms of measuring patterns in variability. A fluorometer measures photons that have been reemitted at a longer wavelength by a molecule that absorbed photons of a shorter wavelength. The amount of energy absorbed or emitted by a particular molecule is a unique characteristic of that molecule. For both of the fluorometers, light is emitted at 470 nm which is a characteristic wavelength for chlorophyll fluorescence. The amount of reflectance returned is a measure of fluorescence. Due to the fact that the fluorometer aboard the Laurence M. Gould is mounted inside the ship in an enclosed device, the diurnal fluctuations in available light do not influence fluorescence measurements. Along with fluorescence, instruments aboard the Laurence M. Gould also record measurements of pressure, temperature, salinity, density, oxygen, wind speed and direction, relative humidity, and  $p\text{CO}_2$ , among other variables.

### **Satellite Estimates of Chlorophyll:**

The satellite estimates that are used in this study are from the Moderate Resolution Imaging Spectroradiometer (MODIS), which is an instrument aboard the National Aeronautics and Space Administration's (NASA) *Aqua* satellite.

*Aqua*'s orbit is a 705 km, sun-synchronous, near polar orbit (Pagano and Durham, 1993). There are several different product levels for the MODIS sensor. Level 1 consists of unprocessed instrument data at full resolution. Level 2 data derives geophysical variables from Level 1 data at the same resolution. Level 3 consists of the same level 2 derived geophysical variables projected onto a "well-defined spatial grid over a well-defined time period" (oceancolor.gsfc.nasa.gov). This study used monthly chlorophyll estimates, level 3 data, from 2012-2015 at 9 km resolution from the NASA ocean color data archive (oceancolor.gsfc.nasa.gov). These estimates are derived from an empirical relationship between in-situ measurements of chlorophyll-a and blue-to-green band ratios of in-situ remotely sensed reflectance. This algorithm requires the use of three or more sensor bands spanning the 440-570 nm spectral range (O'Reilly et al., 1998).

In order to obtain unobstructed measurements of chlorophyll, corrections had to be made to the raw data during processing. These corrections involve separate algorithms that remove the negative effects of features such as clouds or aerosols. When processing from level 1 to level 2, checks are made for different possible conditions that could alter data. When the conditions of a check are met, a flag can be applied to the data. If a flag exists for a pixel and that derived product's quality is determined to be reduced passed a particular threshold, a mask will be applied to that pixel and it will be removed from the valid data and will not



affect analysis (Hooker et al., 2003). Since these masks are applied during the processing of level 1 data, it is impossible to know why a particular pixel or area does not have valid data. In terms of the Southern Ocean, there are several flags that likely could have been applied; including, but not limited to, a failure in atmospheric or aerosol corrections, cloud or ice contamination, and high solar zenith (Hooker et al., 2003). Monthly averaged chlorophyll estimates are used in this study because this averaging scheme reduces the number of masked data points.

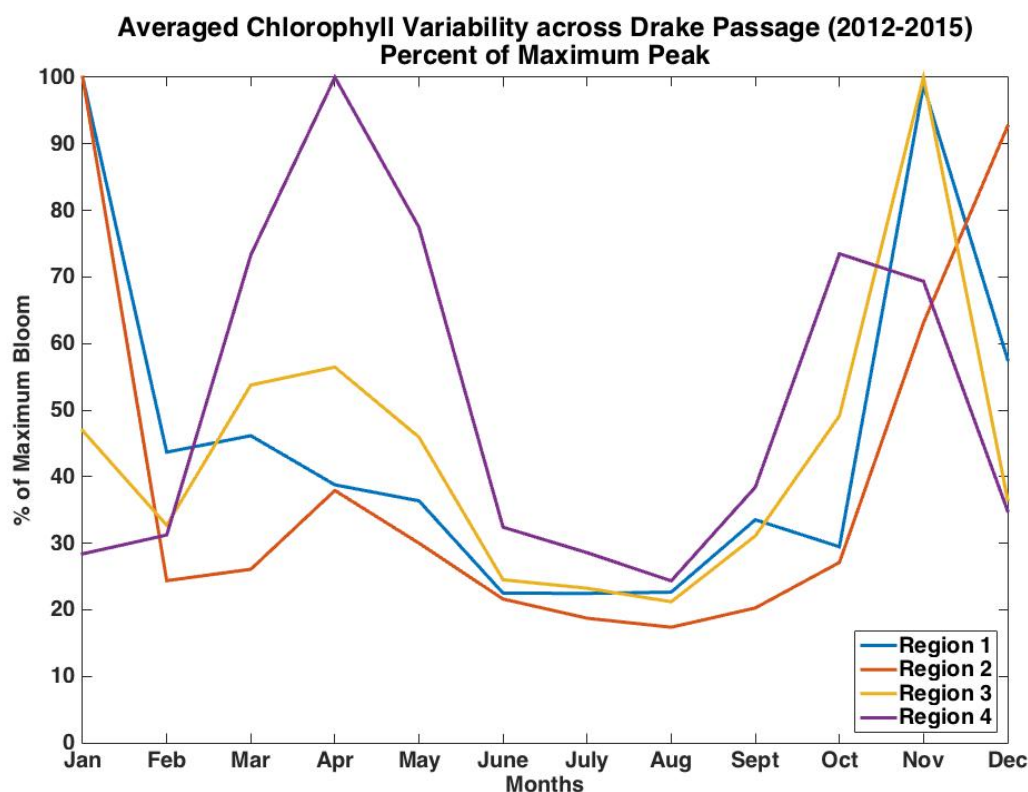
Here, we compare MODIS chlorophyll estimates with the fluorescence derived chlorophyll record. In order to facilitate comparison between these two datasets, it was necessary to re-grid the underway fluorometer data onto the MODIS grid.

## **RESULTS & DISCUSSION:**

### **Austral Fall Bloom**

The seasonal cycle has a substantial influence on the productivity of phytoplankton in the Southern Ocean because of the influence of light and nutrient supply on productivity (Sarmiento and Gruber, 2006). As a result, phytoplankton blooms are typically observed in the austral spring (September-December), when light availability begins to increase and nutrients are plentiful. We examine the

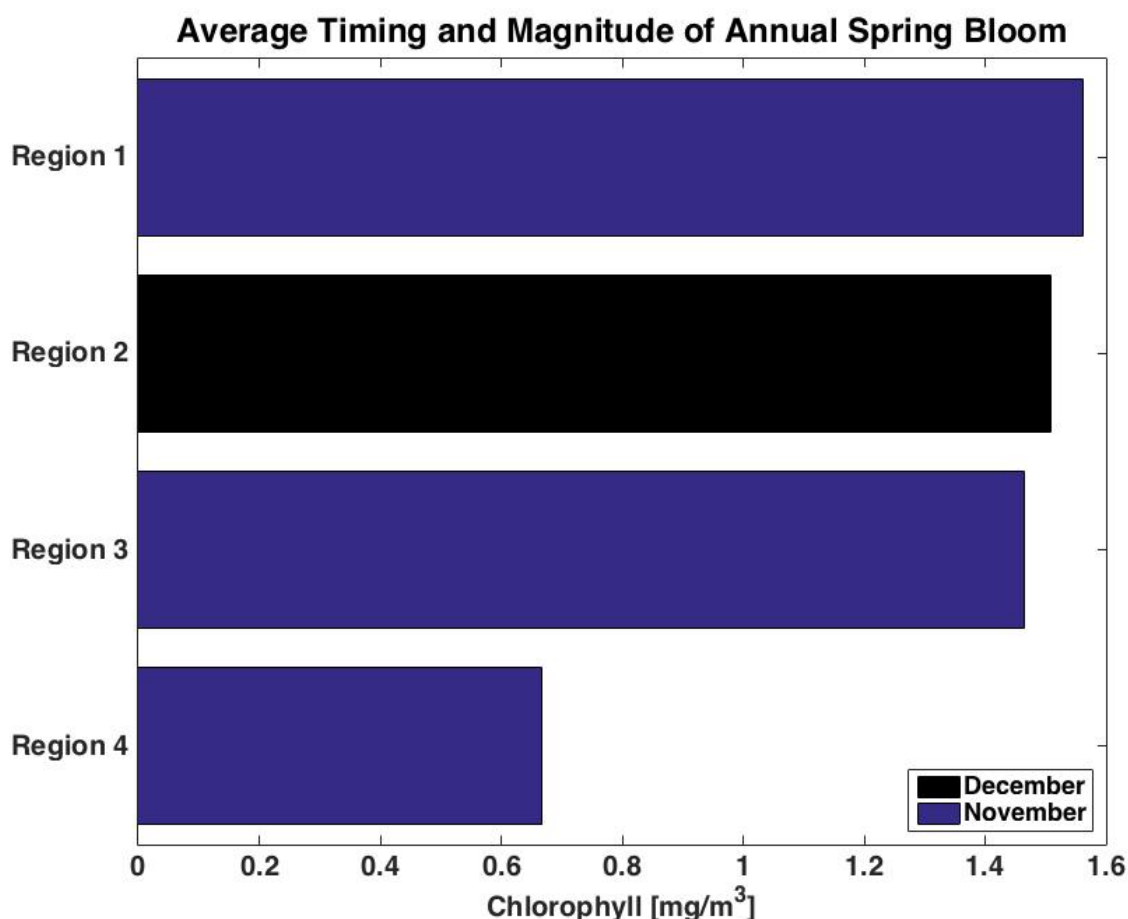
monthly and seasonal variability of underway chlorophyll in Figure 3, where we observe the presence of both a spring and fall bloom.



**Figure 3: Chlorophyll concentration as a percent of the maximum bloom observed from 2012 to 2015. 100% of the maximum bloom is the largest bloom observed for that month. Each data point is a monthly averaged chlorophyll concentration for each of the 4 regions within the Drake Passage.**

The literature suggests that phytoplankton blooms in the Drake Passage occur in the austral spring, because of the influence of seasonal warming on surfaces waters and a developing pycnocline in surface waters (Demidov et al., 2011). The location and magnitude of the spring bloom from our underway dataset

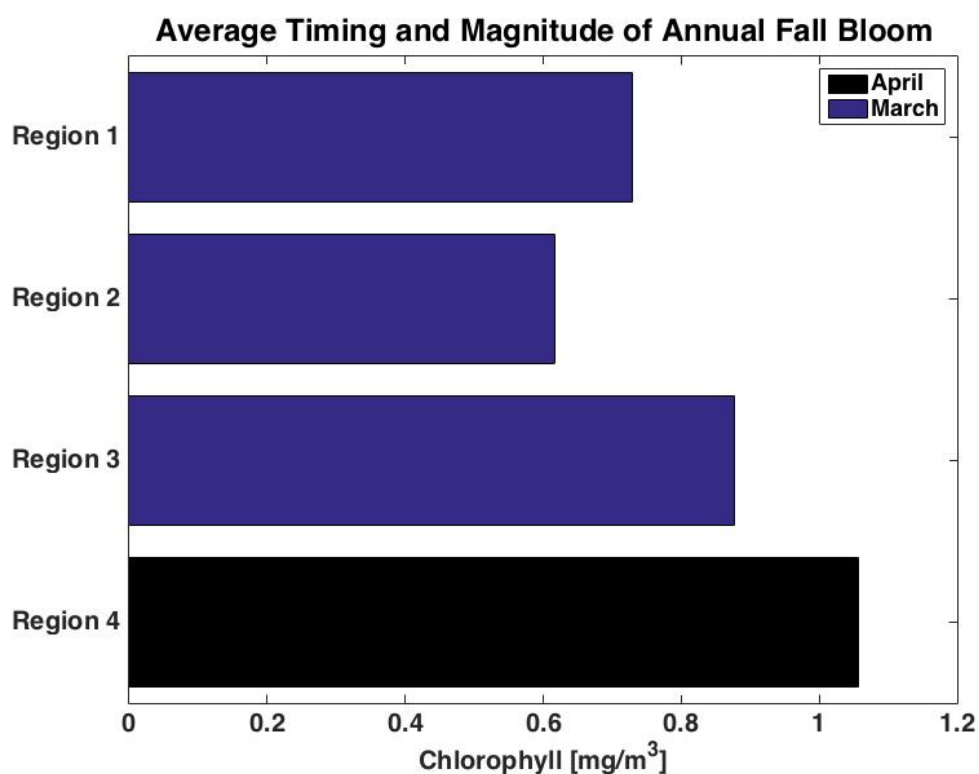
is shown in Figure 4, where we observe the largest spring bloom in the northernmost region, and the latest spring bloom in Region 2.



**Figure 4: Average timing and magnitude of the annual spring bloom observed by the underway fluorometer in each of the 4 regions within the Drake Passage from 2012 to 2015.**

Our finding of an austral fall bloom is significant because of its timing and magnitude. Figures 3, 4, and 5 show that the fall bloom can be as big as (or even bigger than) the spring bloom, with a peak in March or April. This bloom is on the

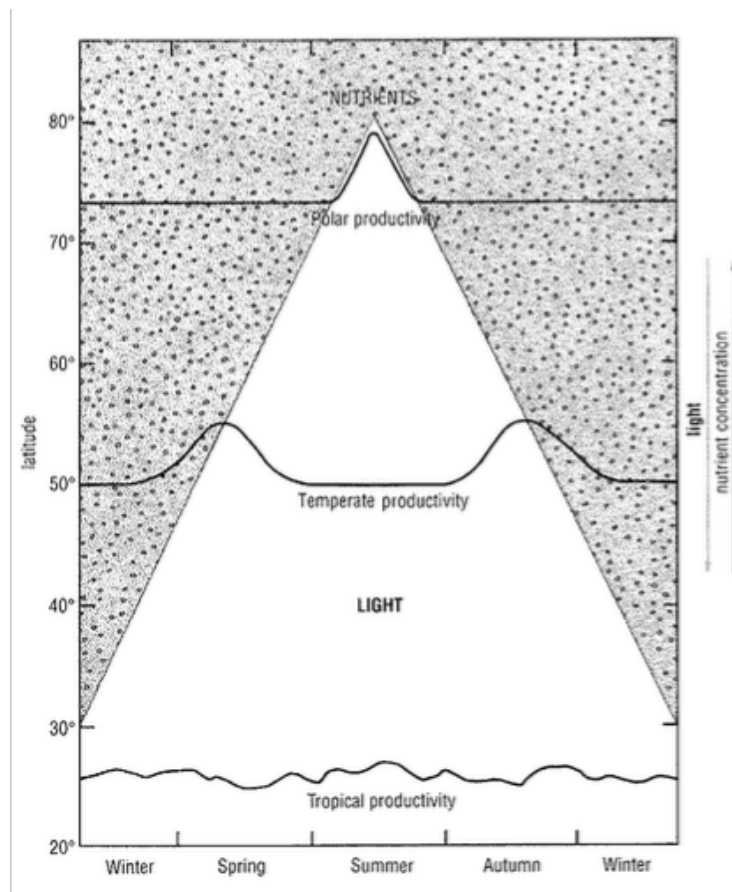
order of 40% to 100% the magnitude of the maximum bloom observed for a given year and region (100% being the maximum bloom observed for that year) as can be seen in Figure 3. The southernmost region of the Drake Passage is associated with the biggest fall bloom. It is interesting to note that this is the same region with the smallest spring bloom.



**Figure 5: Average timing and magnitude of the austral fall bloom observed by the underway fluorometer from 2012 to 2015.**

While not yet observed in the literature, there is precedent for a fall bloom at the mid-to-high latitudes of the Southern Ocean. Here, both light and nutrient availability are likely to play a role in the seasonal cycle of phytoplankton blooms. As shown by the textbook schematic in Figure 6, temperate productivity has two

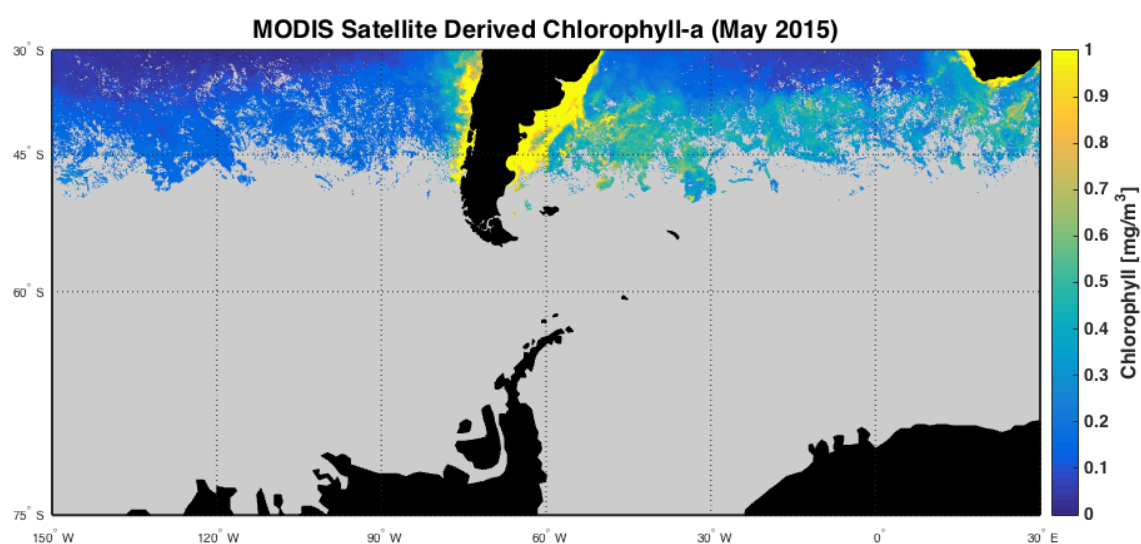
distinct peaks in its climatology: in the spring, when light is becoming plentiful again and nutrient stores are high; and in the fall, when light is still plentiful, and deepening mixed layers resupply nutrients to the mixed layer. Thus, we might expect to find a fall bloom in the Southern Ocean.



**Figure 6: This figure shows how nutrient concentrations and light availability vary as a function of the seasons and latitude from Lalli and Parsons, 1993.**

The fall bloom is especially noteworthy due to its lack of documentation in recent relevant literature. We hypothesize that this is due to current studies reliance on satellite derived estimates of chlorophyll-a rather than in-situ measurements. The fall bloom identified from the underway fluorometer record

typically occurs in March or April. Usually, this is a time when MODIS cannot estimate chlorophyll-a due to the presence of clouds in the Southern Ocean; hence we predict this fall bloom has not been noted for it has not been observed thoroughly. The influence of clouds during the austral fall on MODIS' ability to estimate chlorophyll can be seen in Figure 7, where chlorophyll is shown to be obscured by clouds in May.



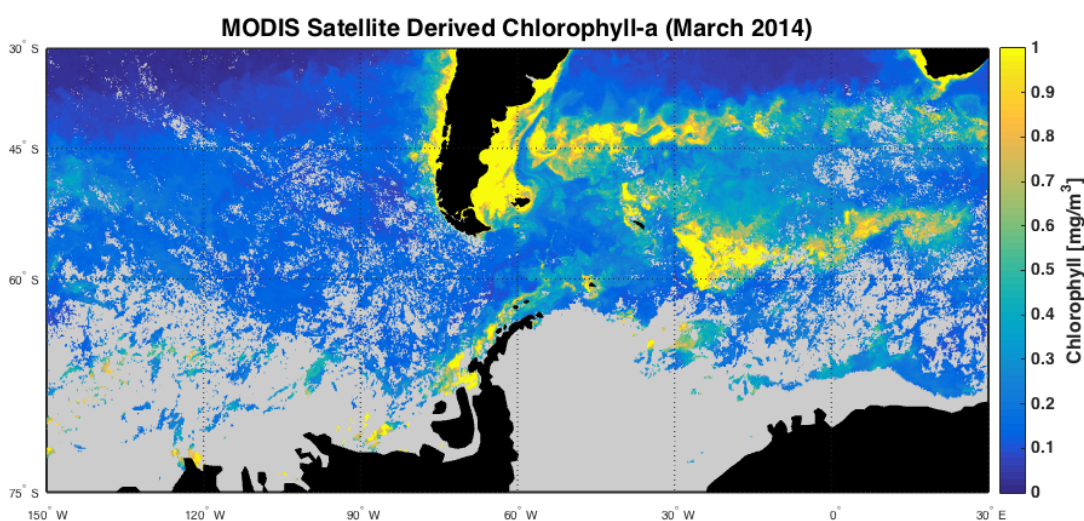
**Figure 7: Estimated chlorophyll concentrations from the MODIS sensor in the Southern Ocean during the month of May. In the Southern Hemisphere, May is a fall month. The hampering influence of clouds can be seen clearly.**

### **MODIS Estimates of Chlorophyll-a**

In order to confirm this hypothesis, we compared MODIS estimates of chlorophyll-a in the Drake Passage with the chlorophyll measurements from the WET Labs fluorometer. This comparison also enabled us to determine if MODIS

possess the ability to capture the same temporal and spatial variability in chlorophyll as the underway fluorometer.

After re-gridding the fluorescence measurements onto the MODIS grid it was clear that this satellite did not possess the same ability or resolution as the underway fluorometer. In fact, from April until August MODIS was not able to produce virtually any estimate of chlorophyll south of about 50° South, especially in the Drake Passage. Furthermore, after comparing MODIS estimates of chlorophyll-a in the months of March and April with the underway fluorometer record, it was clear that MODIS systematically underestimated the magnitude of the fall bloom (Figures 8, 9, Tables 1, 2).



**Figure 8: Estimated chlorophyll concentrations from the MODIS sensor in the Southern Ocean during the month of March. These estimates are underestimates when compared to the underway fluorometer record.**

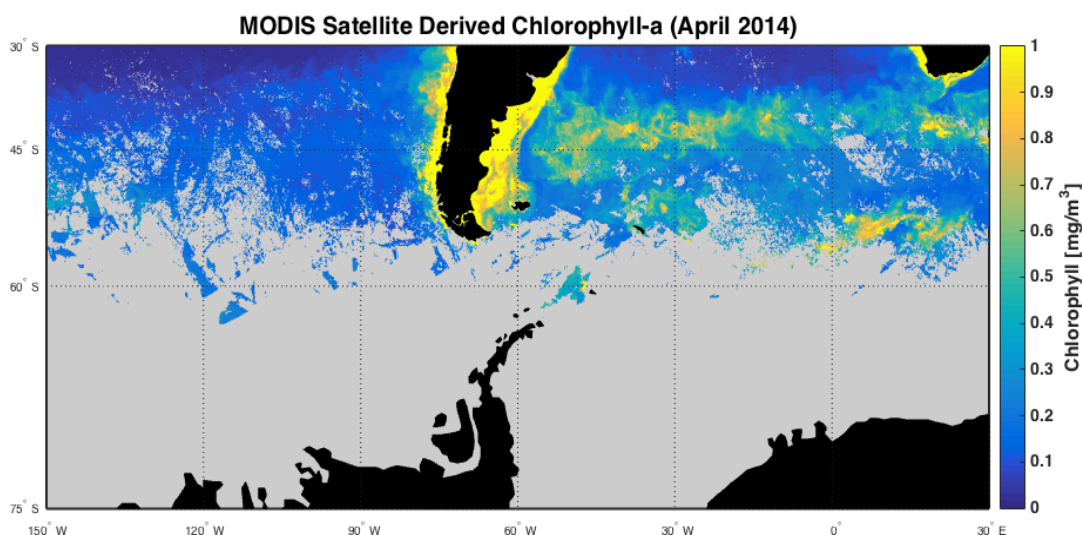


Figure 9: Estimated chlorophyll concentrations from the MODIS sensor in the Southern Ocean during the month of April. It can clearly be seen how these estimates cannot capture the fall bloom due observed by the underway fluorometer due to the hampering influence of clouds.

Average MODIS Estimated Chlorophyll Concentration across the Drake Passage Region of the Southern Ocean [mg/m <sup>3</sup> ]					
Drake Passage Region	2012	2013	2014	2015	2012-2015
Region 1	0.2208	0.2642	0.2043	0.2010	0.2257
Region 2	0.1682	0.1715	0.1876	0.1688	0.1740
Region 3	0.1358	0.1349	0.1482	0.1944	0.1533
Region 4	0.2724	0.1812	0.2235	0.5718	0.3122

Table 1: Yearly averaged estimated chlorophyll concentration from the MODIS sensor throughout the Drake Passage region of the Southern Ocean



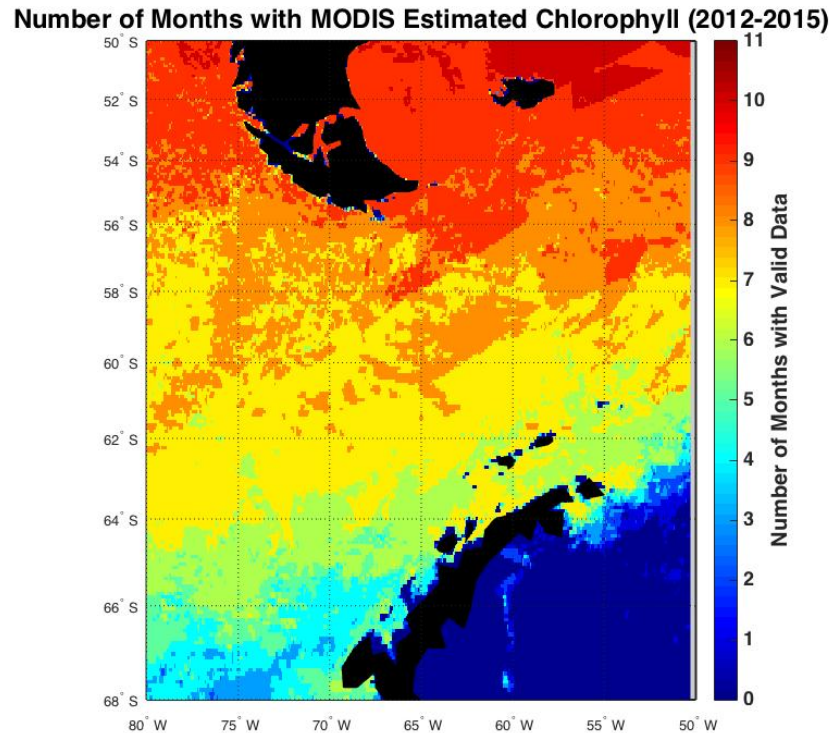
<b>Average Chlorophyll Concentration across the Drake Passage Region of the Southern Ocean [mg/m<sup>3</sup>]</b>					
<b>Drake Passage Region</b>	<b>2012</b>	<b>2013</b>	<b>2014</b>	<b>2015</b>	<b>2012-2015</b>
<b>Region 1</b>	0.740	0.6623	0.8441	0.6646	0.7323
<b>Region 2</b>	0.682	0.5062	0.7737	0.5190	0.6290
<b>Region 3</b>	0.8238	0.5811	0.8350	0.6355	0.7354
<b>Region 4</b>	0.6331	0.5487	0.5056	0.6012	0.5687

**Table 2: Yearly averaged estimated chlorophyll concentration from the underway fluorometer throughout the Drake Passage region of the Southern Ocean**

In fact, MODIS chlorophyll estimates show little to no evidence of a fall bloom at all. The maximum fall bloom observed in the underway fluorometer record occurred, consistently from 2012 to 2015, in region 4 during the month of April, as can be seen in Figure 5. However, from 2012 to 2015, MODIS estimates in the Drake Passage during the month of April were consistently nonexistent so identifying the bloom would be impossible.

To illustrate this further, we calculated the number of months in a year, on average, that MODIS can even make valid estimates of chlorophyll in the Drake Passage region. This can be seen in the Figure 10. Analysis of this figure clearly shows how the number of months with valid estimates decreases as a function of

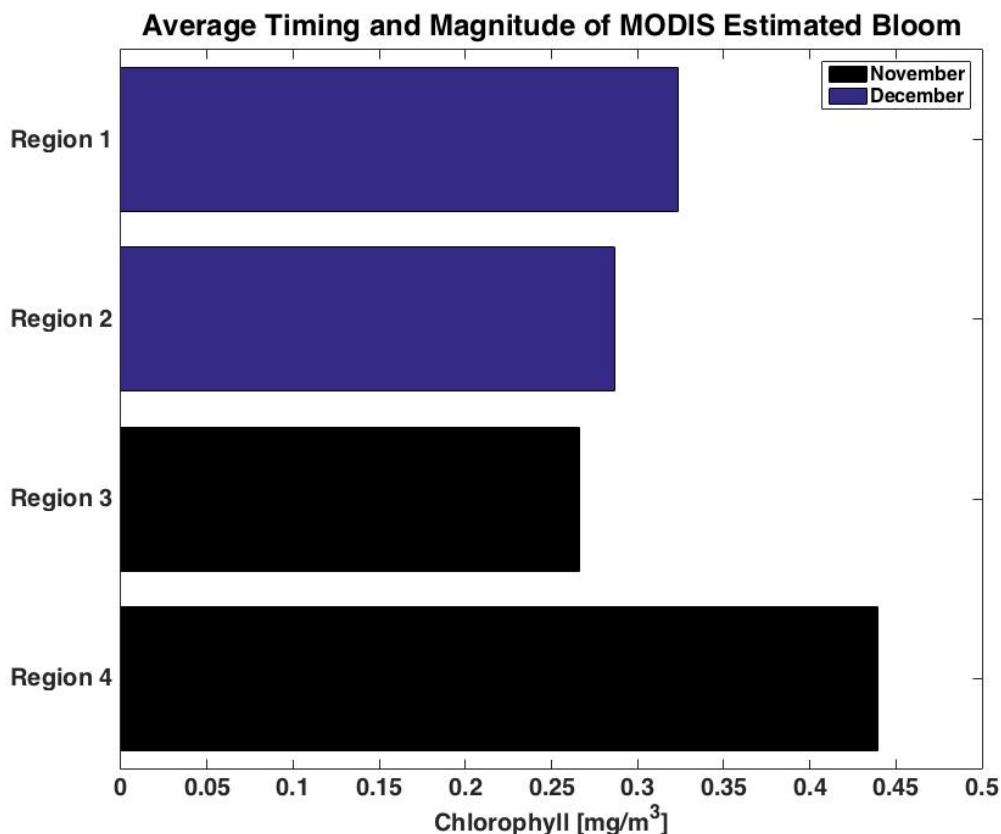
latitude. The cloudy nature of the Southern Ocean is strong support for why this relationship exists.



**Figure 10: Average number of months containing valid MODIS estimates of chlorophyll in the Drake Passage from 2012 to 2015.**

While MODIS estimates of chlorophyll were not able to capture the fall bloom observed by the underway fluorometer, the satellite was able to capture a distinguishable bloom in the austral spring. Although again when compared with the underway fluorometer, MODIS significantly underestimated the chlorophyll concentration in the spring bloom. The average timing and magnitude of the bloom observed by MODIS can be seen in Figure 11. The difference in magnitude

between this bloom and the austral spring bloom observed by the underway fluorometer can be seen through comparison of this figure with Figure 4.



**Figure 11: Average timing and magnitude of the spring bloom observed in the MODIS estimated chlorophyll record from 2012 to 2015. It can be seen how the magnitude of this bloom is significantly less than the austral spring bloom observed by the underway fluorometer.**

### **pCO<sub>2</sub> in relation to Chlorophyll and Photosynthesis**

We compared underway chlorophyll measurements with simultaneous surface ocean pCO<sub>2</sub> in the Drake Passage. We might expect to find an anti-correlation between chlorophyll and pCO<sub>2</sub>, since phytoplankton photosynthesis uses dissolved CO<sub>2</sub> (see carbonate chemistry discussion in the next paragraph).

Figures 12 and 13 show the spatial and temporal variability of  $p\text{CO}_2$  and chlorophyll across the Drake Passage, respectively from 2012 to 2015. There is a small negative correlation between chlorophyll and  $p\text{CO}_2$  (Percent variance explained = 1.63%, Significance = 100).

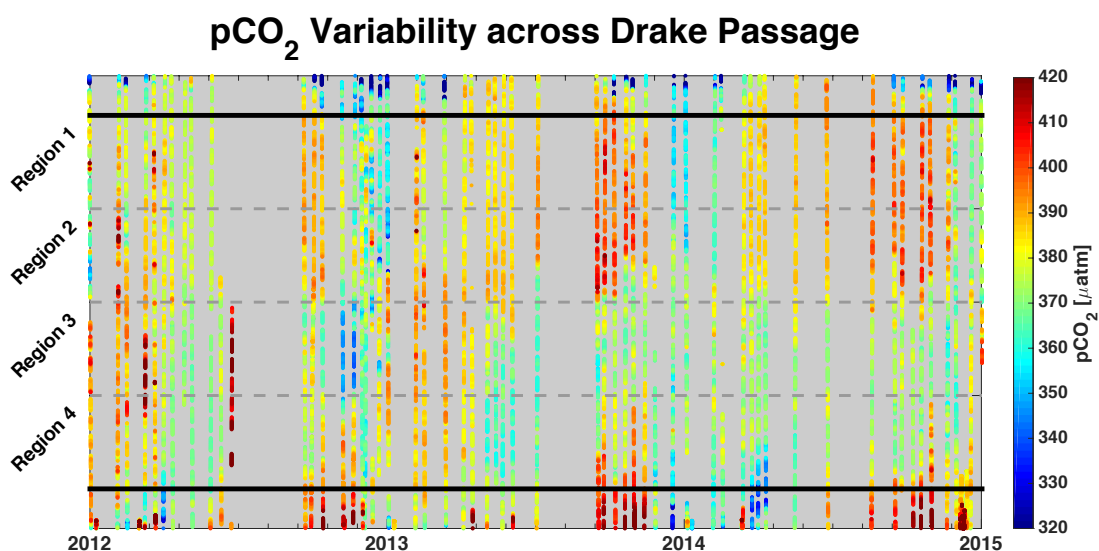


Figure 12:  $p\text{CO}_2$  variability across the Drake Passage was calculated for all of the crossings from 2012 to 2015.

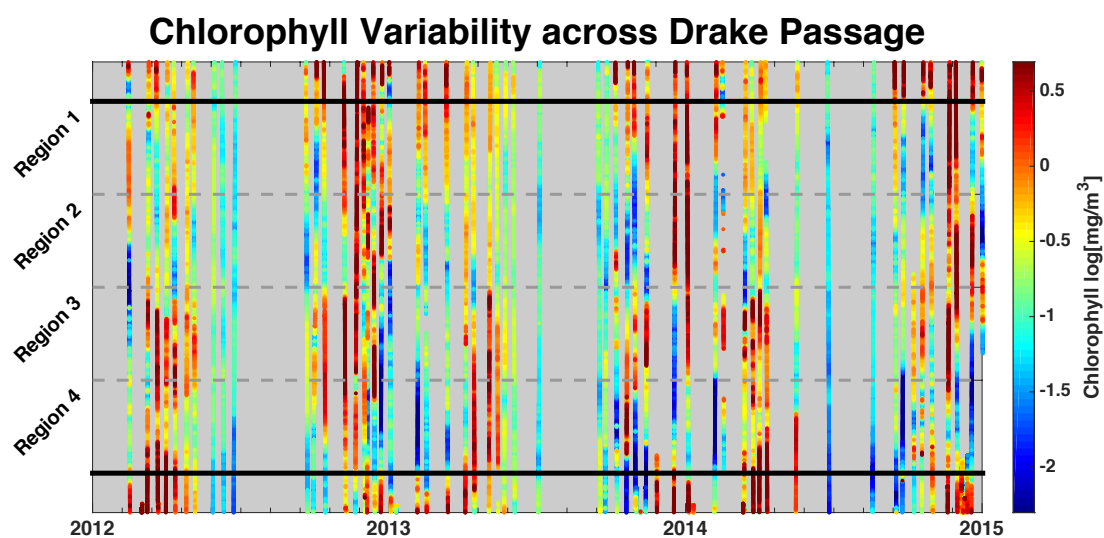


Figure 13: Chlorophyll variability across the Drake Passage region was calculated for all of the crossings from 2012 to 2015.

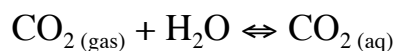
In order to understand why we observe a weak relationship between chlorophyll and  $p\text{CO}_2$  in the Drake Passage, it is important that we describe how photosynthesis alters seawater chemistry. Photosynthesis is essentially the conversion of inorganic compounds into organic compounds. During photosynthesis, light energy is converted into chemical energy in the presence of water, which also causes the release of oxygen. This chemical energy is then used to fix  $\text{CO}_2$  into organic matter. Chlorophyll is the molecule responsible for absorbing energy from incoming sunlight during photosynthesis. The chemical reaction for photosynthesis can be seen in equation 1 (Sarmiento and Gruber, 2006).

**Equation 1:**



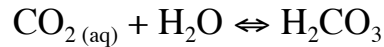
As for how photosynthesis alter seawater chemistry, when gaseous  $\text{CO}_2$  dissolves in seawater inorganically, it first gets hydrated to form aqueous  $\text{CO}_2$  or  $\text{CO}_{2(\text{aq})}$  as can be seen in equation 2 (Sarmiento and Gruber, 2006).

**Equation 2:**

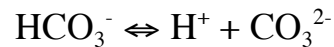
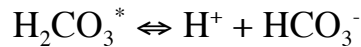


Following this step,  $\text{CO}_{2(\text{aq})}$  then reacts with water to form carbonic acid or  $\text{H}_2\text{CO}_3$  as can be seen in equation 3 (Sarmiento and Gruber, 2006).

### Equation 3:



Since it is hard to distinguish between  $\text{CO}_{2(\text{aq})}$  and  $\text{H}_2\text{CO}_3$  in seawater, these two species are typically combined and the sum is expressed as the hypothetical species  $\text{H}_2\text{CO}_3^*$ . This hypothetical species often dissociates in seawater in two steps to form bicarbonate, or  $\text{HCO}_3^-$ , and carbonate, or  $\text{CO}_3^{2-}$ , as can be seen below (Sarmiento and Gruber, 2006).



This combined species of  $\text{H}_2\text{CO}_3^*$  is often related to  $p\text{CO}_2$ , the partial pressure of  $\text{CO}_2$  in seawater by an equilibrium constant  $K_o$ , as can be seen below (Sarmiento and Gruber, 2006).

$$K_o = \frac{[\text{H}_2\text{CO}_3^*]}{p\text{CO}_2}$$

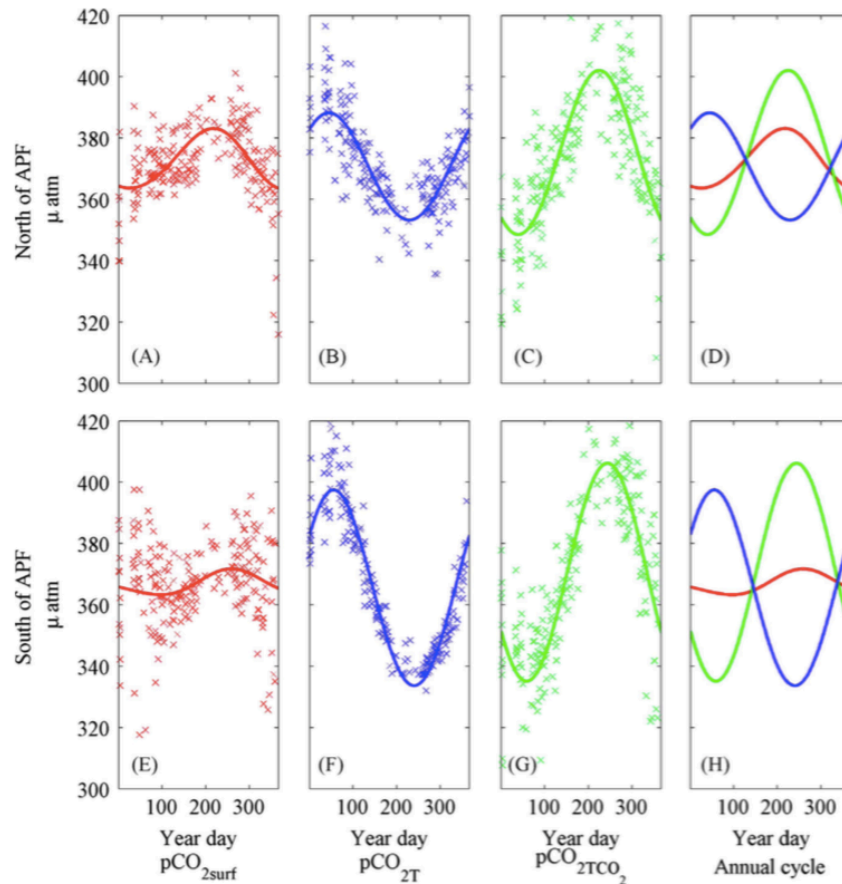
The sum of these different species of inorganic carbon in seawater is referred to as dissolved inorganic carbon (DIC), as can be seen below (Sarmiento and Gruber, 2006).

$$\text{DIC} = [\text{H}_2\text{CO}_3^*] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}]$$

From the chemical equation for photosynthesis, see equation 1, it can be seen how the process of photosynthesis consumes  $\text{CO}_2$ . In terms of phytoplankton

in seawater, this is an important (theoretical) inverse relationship between  $p\text{CO}_2$  and chlorophyll. The more phytoplankton perform photosynthesis, the more chlorophyll and the less  $p\text{CO}_2$  in seawater.

However, there is also a thermally driven component that controls  $p\text{CO}_2$ . As waters warm, the component of  $p\text{CO}_2$  that is thermally controlled increases in concentration and vice versa (Munro et al., 2015). This is because as the temperature increases the solubility constant for  $p\text{CO}_2$ ,  $K_o$ , decreases. The biological and thermal components of  $p\text{CO}_2$  are governed largely by the seasons. Summer warming contributes to the thermal component of  $p\text{CO}_2$  and also the biological in the sense that more photosynthesis is being performed in the presence of increased available sunlight. Therefore, these components of  $p\text{CO}_2$  actually work against one another and reduce seasonal variability. As a result, it is expected that there is a low correlation between  $p\text{CO}_2$  and chlorophyll. Figure 14 shows the opposing affect of these two components. Thus, we might not expect to see a large or significant correlation between  $p\text{CO}_2$  and chlorophyll in the Drake Passage due to a cancellation between the thermal and non-thermal (i.e. circulation and biological) components of  $p\text{CO}_2$ .



**Figure 14: The seasonal cycle of  $p\text{CO}_2$  (red line) north and south of the Antarctic Polar Front. It is separated into a thermally-driven component (blue line) and a  $\text{TCO}_2$  driven component (green line). The opposing effects of these different components can be seen in the red line. Figure from Munro *et al.* 2015.**

## Underway Fluorometer Variability

While the presence of an austral fall bloom in this underway fluorescence data set is the most remarkable finding, the basic variability this underway fluorometer is able to capture is noteworthy as well. Table 3 shows the overall spatial and temporal variance of chlorophyll, as estimated by the underway fluorometer, where variance is different from year to year and region to region.



<b>Variance in Chlorophyll Concentration across the Drake Passage Region of the Southern Ocean [mg/m<sup>3</sup>]</b>					
<b>Drake Passage Region</b>	<b>2012</b>	<b>2013</b>	<b>2014</b>	<b>2015</b>	<b>2012-2015</b>
<b>Region 1</b>	0.0045	0.175	0.403	0.176	0.333
<b>Region 2</b>	0.0055	0.152	0.556	0.239	0.412
<b>Region 3</b>	0.0057	0.078	0.338	0.107	0.380
<b>Region 4</b>	0.0070	0.095	0.335	0.121	0.259
<b>Drake Passage</b>	0.0057	0.125	0.408	0.160	0.346

**Table 3: Variance in chlorophyll concentration from the underway fluorometer throughout the Drake Passage region of the Southern Ocean**

## **CONCLUSION:**

The underway fluorescence time-series from the Antarctic Research and Supply Vessel Laurence M. Gould is unprecedented in terms of its duration and year-round coverage. In this study we utilized chlorophyll measurements derived from two different underway fluorometers and satellite derived estimates of chlorophyll-a from the MODIS sensor aboard NASA's *Aqua* satellite in order to quantify spatial and temporal variability in the surface chlorophyll in the Drake Passage region of the Southern Ocean.

Examination and comparison of the underway fluorometer data set revealed a weak statistical relationship between  $p\text{CO}_2$  and chlorophyll. This relationship was expected as chlorophyll serves as a proxy for the processes of photosynthesis, which consumes  $\text{CO}_2$ . This correlation is expected to be particularly weak because the amplitude of the seasonal cycle in  $p\text{CO}_2$  is diminished by the negating effects of the seasonal cycles in the different components of  $p\text{CO}_2$ . Furthermore, analysis of averaged monthly chlorophyll concentration throughout the Drake Passage region revealed the presence of an austral fall bloom. The presence of this bloom was particularly intriguing because phytoplankton blooms in the Drake Passage typically occur in the austral spring due to the influence of seasonal warming on surface waters and a developing pycnocline (Demidov et al., 2011). However, this bloom was significant enough to deserve further investigation due to the fact that it was on the order of 40% to 100% of the magnitude of the maximum bloom observed for a given year and region. This fall bloom is especially noteworthy due to its lack of documentation in recent relevant literature. We hypothesized this could be attributed to recent studies reliance on satellite derived estimates of chlorophyll-a rather than in-situ measurements. Mainly, this is because this austral fall bloom occurred during months where satellite estimates of chlorophyll-a are particularly hampered due to the presence of clouds.

Analysis of MODIS estimates of chlorophyll-a confirmed this hypothesis. MODIS estimates of chlorophyll-a showed little to no evidence of a fall bloom. In fact, consistently, from April until August MODIS was not able to produce virtually any estimate of chlorophyll South of about 50° South. During the months where the austral fall bloom peaked in the underway fluorescence record, MODIS steadily underestimated chlorophyll concentration.

While phytoplankton may seem insignificant due to their small size, the implications for changes in their abundance are far reaching. Phytoplankton are essentially the main component of what is referred to as the biological pump. The biological pump refers to the processes that transfer carbon from the atmosphere to the deep ocean. Globally, the biological pump transfers about 10 Pg ( $1 \times 10^{13}$  kg) of carbon per year from the atmosphere to the deep ocean (Bopp et al., 2005). Because this is a significant portion of the global carbon cycle it is important to continue to study and monitor phytoplankton, especially in the Southern Ocean. Slight alterations in phytoplankton productivity have the potential to affect atmospheric CO<sub>2</sub> levels which have a strong influence on global surface temperatures.

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